Muon Collaboration

Absorber R&D

Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY

Transforming Lives.Inventing the Future.www.iit.edu

ICAR

NuFact ’01 Workshop
Tsukuba, Japan
May 28, 2001

MuCool Absorber R&D Collaboration:

E. Almasri, E. L. Black, K. Cassel, R. Johnson, D. M. Kaplan, W. Luebke
*Illinois Institute of Technology**

S. Ishimoto, K. Yoshimura
KEK High Energy Accelerator Research Organization

M. A. Cummings, A. Dychkant, D. Hedin, D. Kubik
*Northern Illinois University**

C. Darve†
*Northwestern University**

Y. Kuno
Osaka University

D. Errede, M. Haney
*University of Illinois at Urbana-Champaign**

M. Reep, D. Summers
University of Mississippi

in collaboration with

S. Geer, C. Johnstone, M. Popovic, A. Tollestrup
Fermilab

*member, Illinois Consor tium for Accelerator Research

†also at Fermilab

Main Issues

- Need to:

1. Minimize scattering-induced beam heating
   - Use LH_2
   - Use as thin and low-*Z* windows as practical
2. Remove large *dE/dx* heat flux
   - Need to understand fluid flow and heat transfer
3. Prototype and test to verify designs
   - Complicated engineering issues require empirical tests
   - Both bench and beam tests planned

- New idea: gaseous absorber
- How to build shaped absorbers?

Absorbers & Power Dissipation

- Baseline Feasibility Study II design has 3 types of absorbers:

Absorber	Length (cm)	Radius (cm)	Window thickness (μm)	Number needed	Power diss. (W)
Minicool	175	30	≈300	2	≈ 5500
SFOFO 1	35	18	360	16	≈ 300
SFOFO 2	21	11	220	36	≈ 100

- SFOFO absorber ~ 100 W

  ⇒ Lineal power density ≈ 5–10 W/cm

  → comparable to high-power LH_2 targets
  (*cf*. SLAC, Bates, JLab)

- But note: Palmer's × 2 in efficiency, × 4 in *p* beam power would require × 8 in cryo & power handling

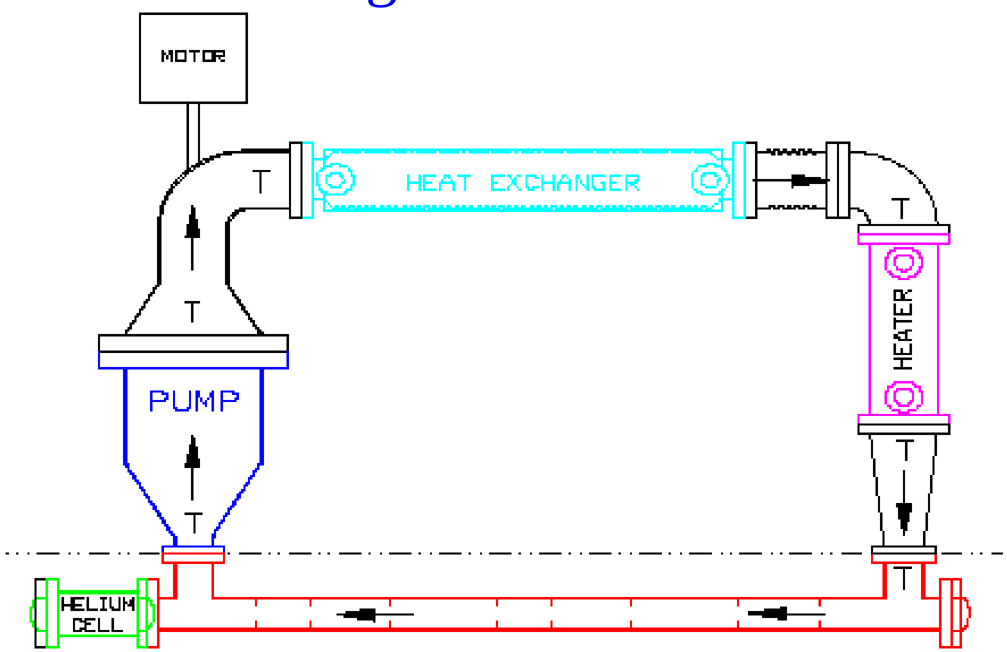
Heat Transfer

- Need to assure adequate heat transfer from core to periphery

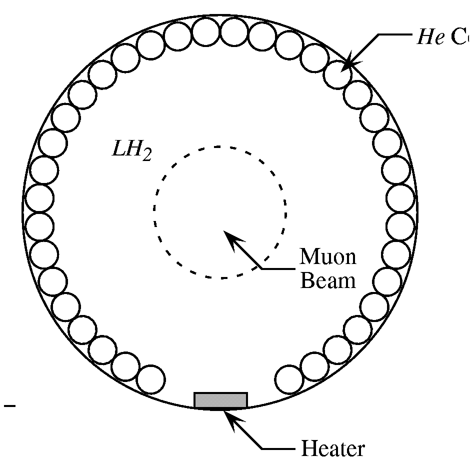
  ⇒ Avoid longitudinal flow

- 2 approaches:

  1. Flow-through



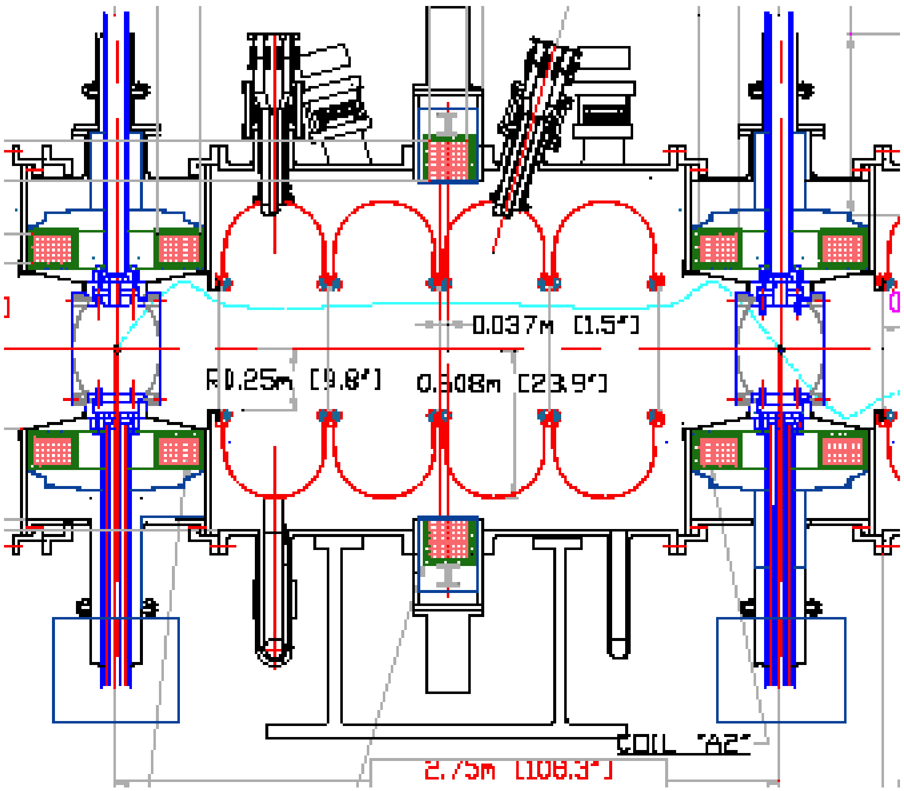
  2. Convection



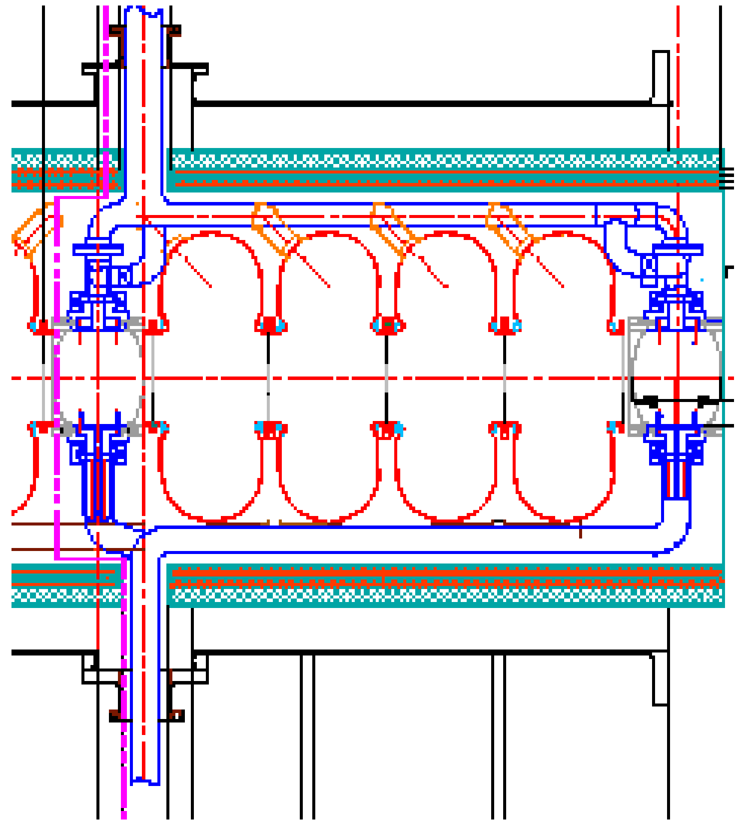
- Both appear feasible – further studies & tests in progress

Cooling-Channel Layouts

SFOFO, 2.75-m lattice



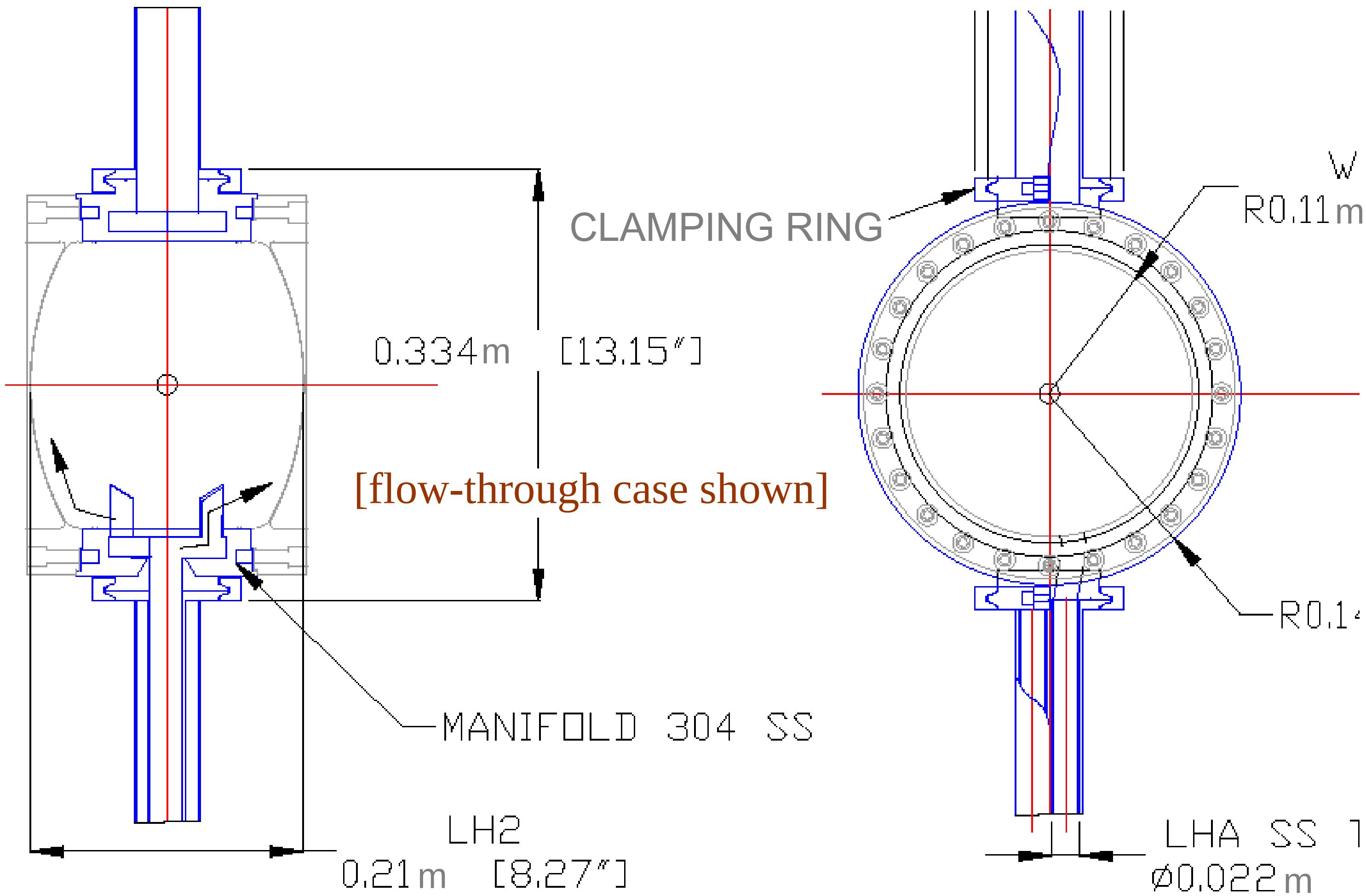
Double-Flip



⇒ To maximize cooling rate & minimize solenoid cost, need absorber design that fits in cramped space

SFOFO 2 Absorber Assembly

(E. L. Black, IIT)



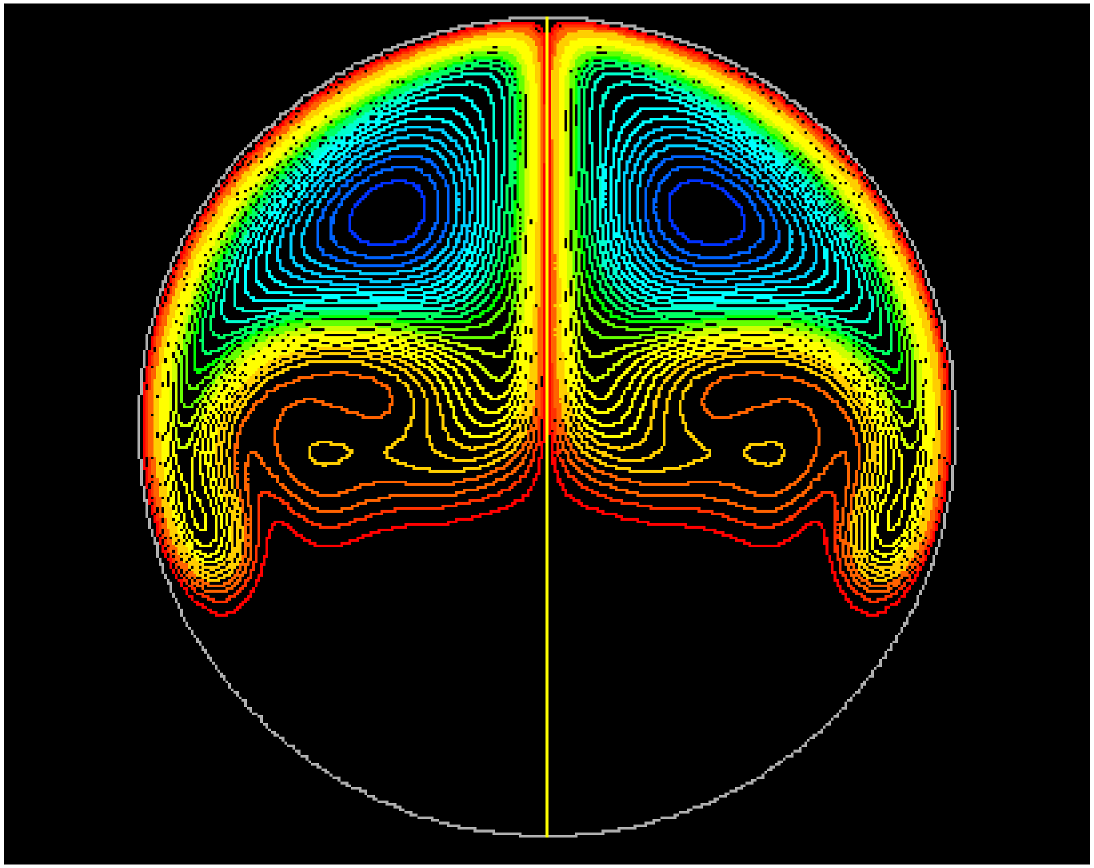
- Nozzles that determine flow pattern need to be designed and tested heuristically

→ Will bench-test this with room-temperature flow model

Convection Design

(E. Almasri, K. Cassel, IIT; S. Ishimoto, K. Yoshimura, KEK; Y. Mori, Osaka)

- Performance more amenable to calculation than for flow-through,
  - key question: convective heat transfer coefficient within LH_2
- 2D CFD calc by IIT engineering M.S. student (3D calc impractical):



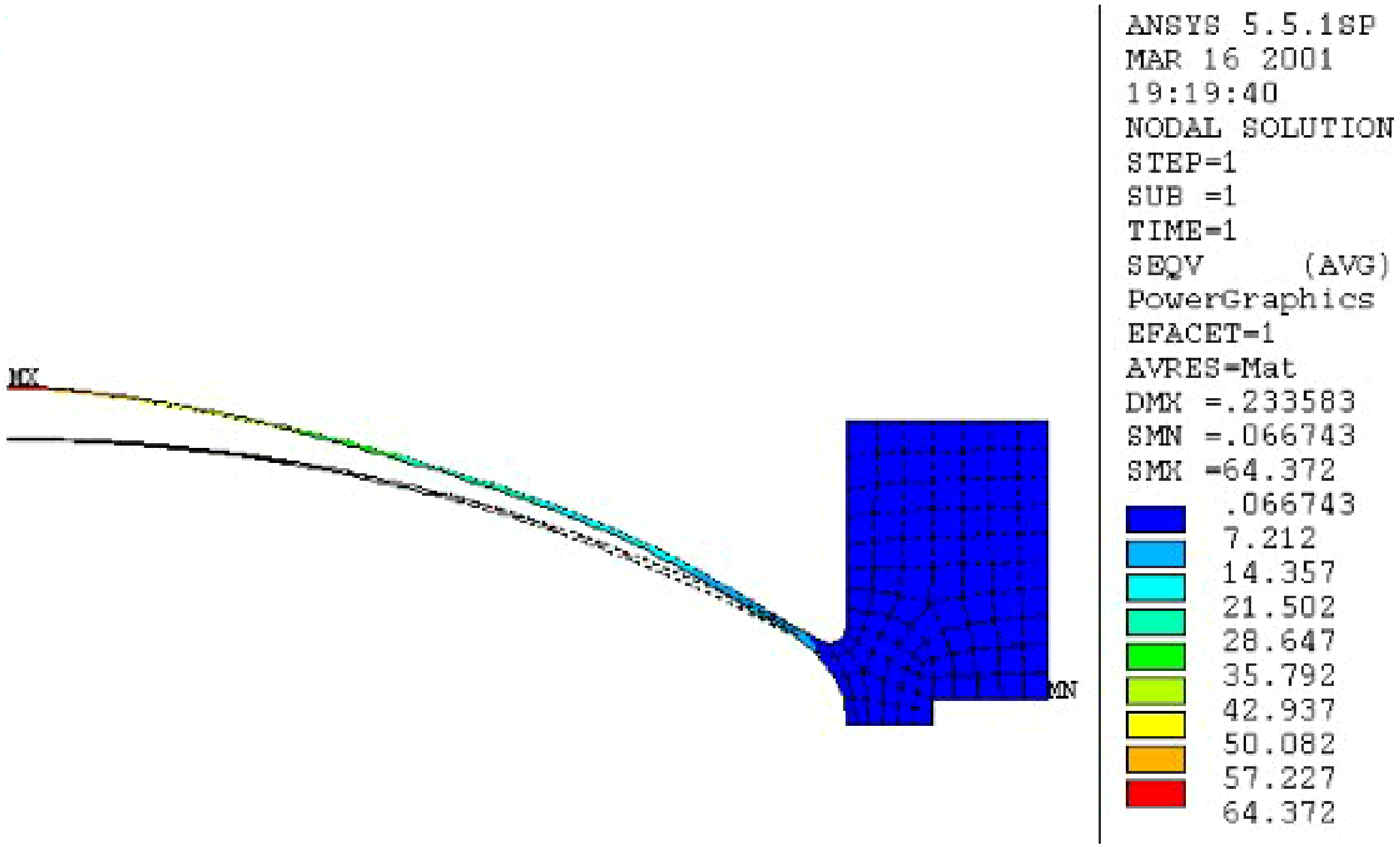
  - Refinement of CFD calcs ongoing
- KEK-Osaka group building prototype

Minimizing Window Thickness

(E. L. Black, IIT; M. A. Cummings, NIU; C. Darve, NWU)

- ASME: $t \geq \dfrac{0.885PD}{SE - 0.1P} = \begin{cases} 530\,\mu\text{m } (D = 36\text{ cm}) \\ 330\,\mu\text{m } (D = 22\text{ cm}) \end{cases}$ *(torispherical, 6061-T6, P = 1.2 atm)*

- ANSYS F.E.A. study (C. Darve, NWU) shows that *tapered* 6061-T6 Al torispherical window of 360-µm (220-µm) thickness and 36-cm (22-cm) diameter safe at 1.2 atm:



Thinner Windows?

(D. Summers, U. Miss.)

Al alloy name	**Composition**	**Density**	**Yield strength @300K**	**Tensile strength @300K**	**Tensile strength @20K**	**Rad. Length**
	% by weight	(g/cc)	(ksi)	(ksi)	(ksi)	(cm)
6061-T6	1.0Mg 0.6Si 0.3Cu 0.2Cr	2.70	40	45	68	8.86
2090-T81	2.7Cu 2.2Li .12Zr	2.59	74	82	120	9.18

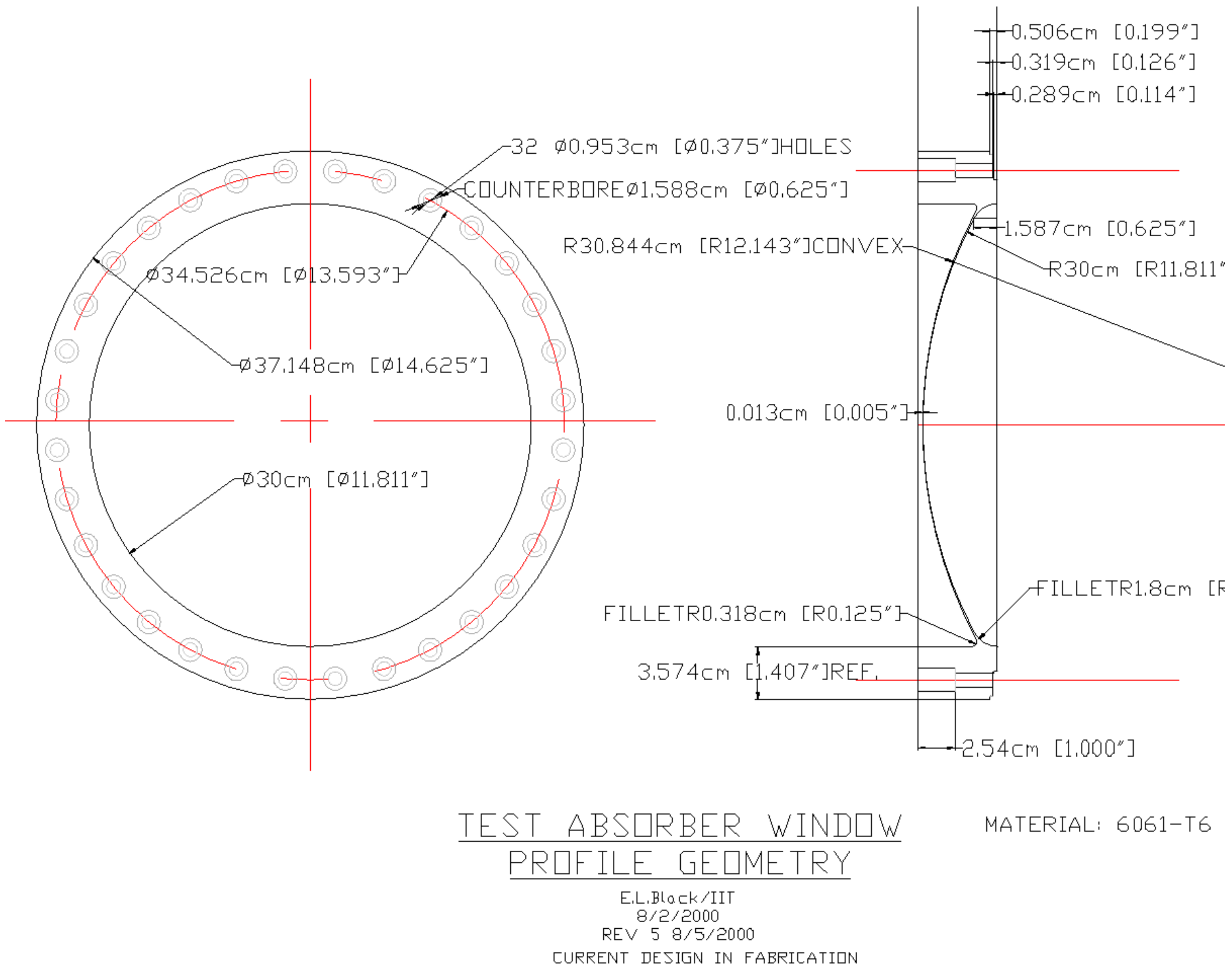
- “Aircraft alloy” 2090-T81 80% stronger than 6061-T6

$\Rightarrow$ Thickness can be reduced by ≈ 45%

$\Rightarrow$ 200 µm thickness at 18-cm radius
125 µm thickness at 11-cm radius
at 1.2 atm

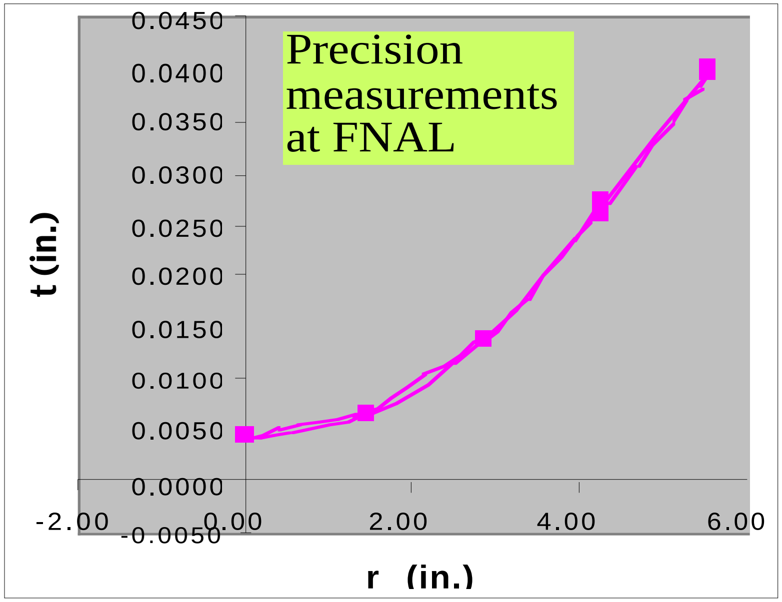
IF design scales ≈ linearly and
IF such thin foils can be manufactured from this material (U. Miss. to test)

Prototype Window Design

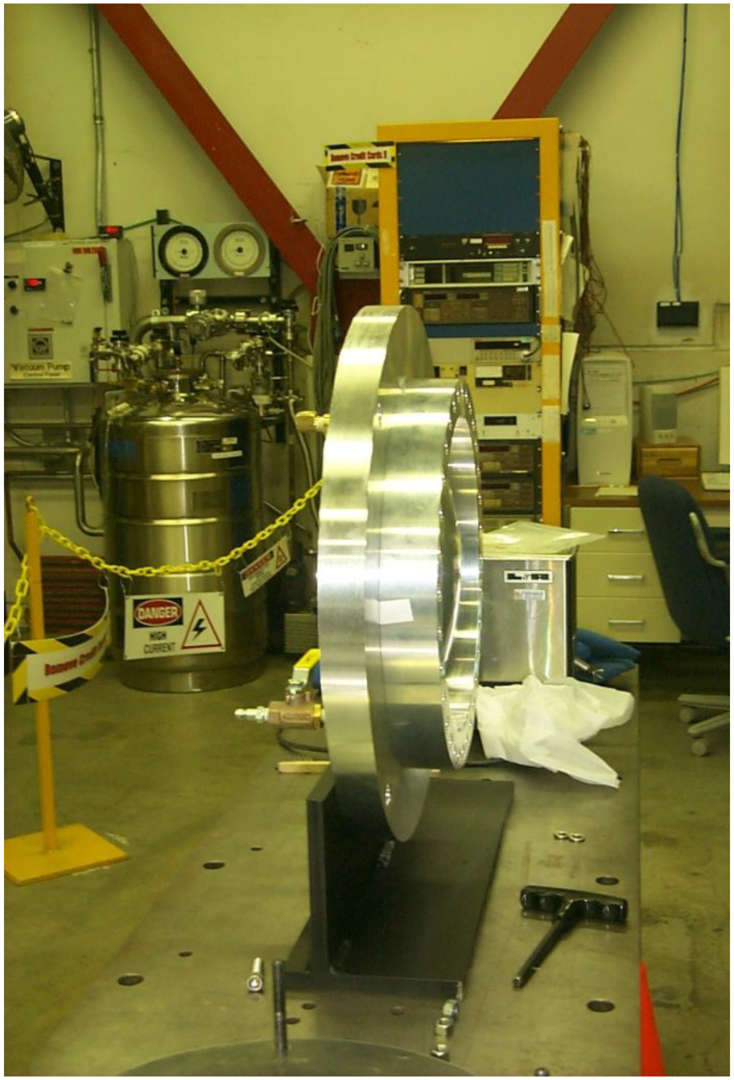


Prototype Window – as built

- Window machining at U. Miss.

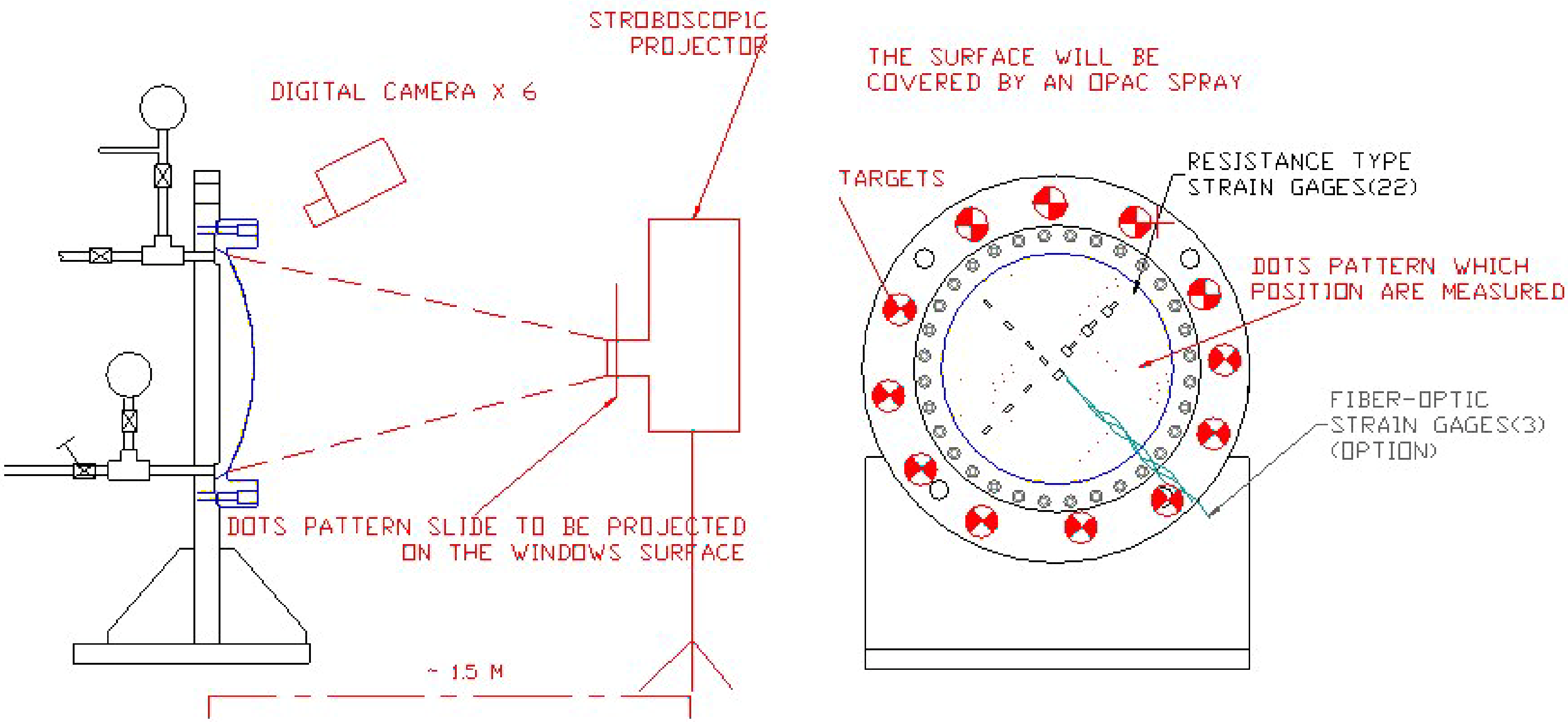


- Setup for pressure test at NIU



Window Overpressure Test

- Pressurize window prototype with H_2O to certify F.E.A. calculation
- To take place later this month
- Monitoring techniques:
  - Strain gauges
  - High-speed photography
  - ΔV (observe change in H_2O height in graduated cylinder)
  - Photogrammetry:



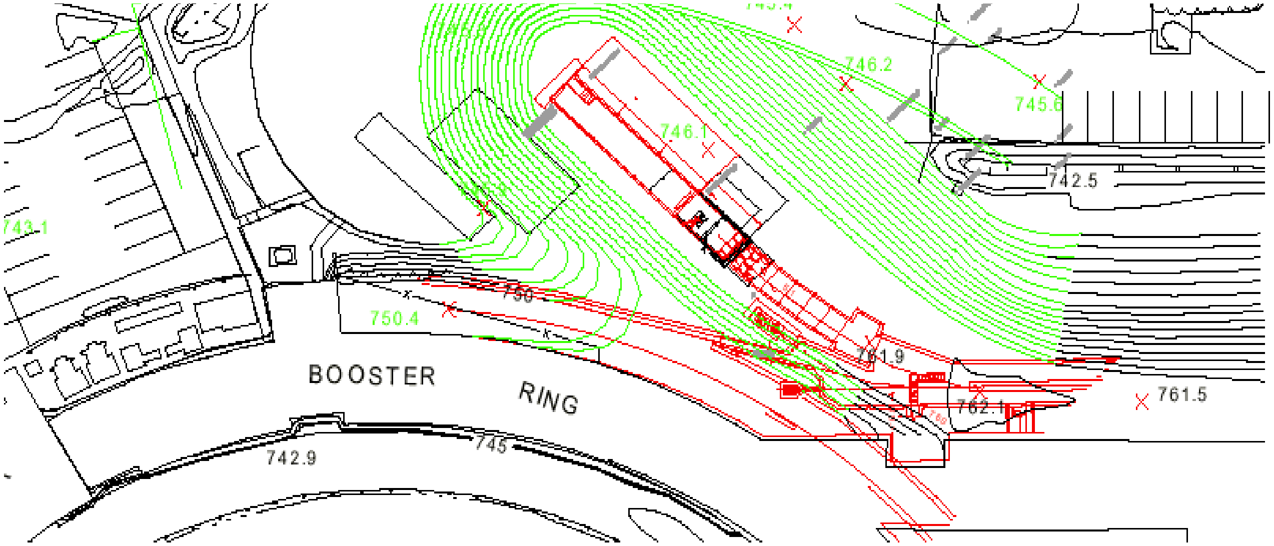
WINDOW PRESSURE TEST SETUP W/ ITS INSTRUMENTATION

C L Black IIT 11/15/2000
Ch Darve NWU 4/20/01

Linac-area Test Facility (LTF)

- View to southwest from Wilson Hall showing parts of Linac berm and gallery and parking lot

- Layout of new construction



LTF Program

Current status and plans:

- Construction in progress
- LH_2-absorber bench tests to start this summer
- Beamline installation over next year
- High-power absorber beam tests next year, beam tests of integrated cooling cell in a few years (once 201-MHz cavities & solenoid available), followed by “string test”
  - Note max power density 16 W/cm – insufficient for “Palmer upgrade”
- High-power RF testbed (both 200 MHz and 805 MHz)

Options for the future:

1. Superconducting RF test facility, *e.g.*:

   200 MHz superconduting cavity (Cornell)

   805 MHz cavity for Linac energy upgrade

2. Any H^- 400-MeV-beam-related experiment

Minicooling Absorbers

- FS II calls for 2 minicooling absorbers preceded by beryllium plate (to absorb low-*E* protons):

Absorber	Mat'l	Length (cm)	Radius (cm)	Power Diss. (kW)
"0"	Be	1?	30	?
1	LH_2	175	30	≈5.5
2	LH_2	175	30	~5

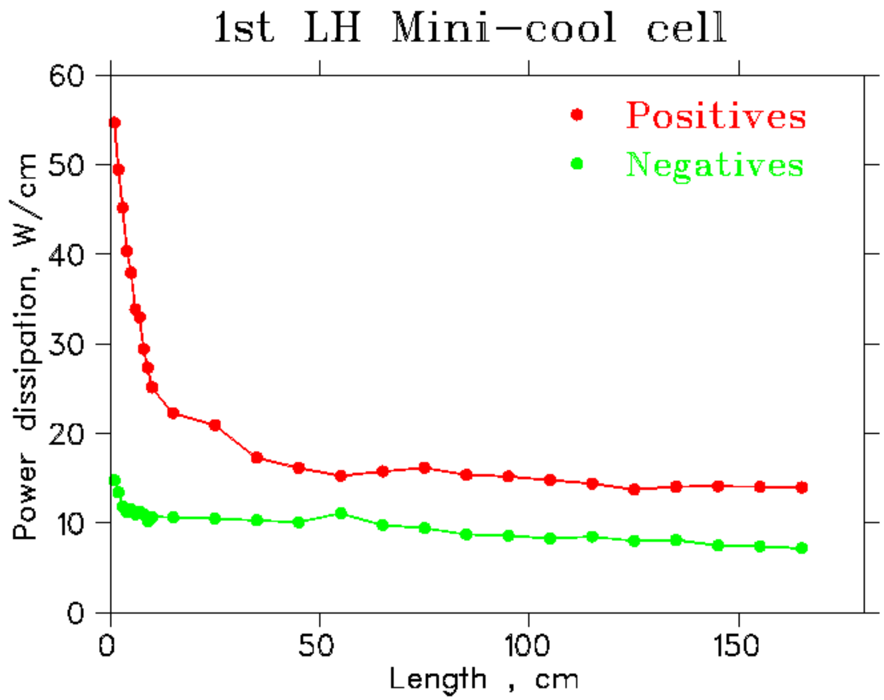
- FNAL 15´ bubble chamber had 6.7-kW refrigerator

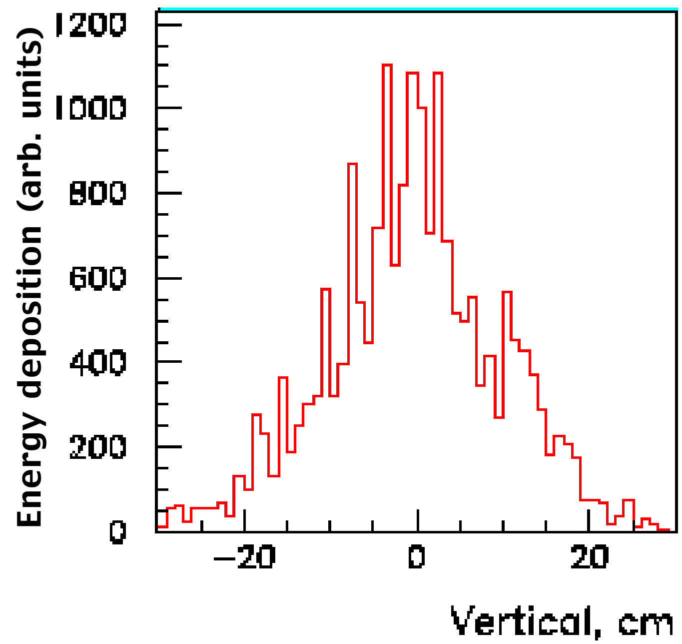
  ⇒ 5.5-kW absorber feasible (known technology), not too expensive (~ $\$10^6$ capital, ~ $\$10^5$/y operating)

- Note that minicooling dominates cooling-channel cryo!
  - Minicooling: ≈ 11 kW
  - SFOFO 1: ≈ 4.8 kW
  - SFOFO 2: ≈ 3.6 kW

Minicooling: Heat transfer

- Peak dissipation much higher than average (H. Kirk sims):





$\Rightarrow$ Need to assure adequate heat transfer from core to periphery

Haven't worked this out in detail. Note that power/cm at upstream end is $>10\times$ that proposed for SLAC E158, but power/cm^3 is $<10^{-2}\times$E158

$\Rightarrow$ Looks feasible

Minicooling: Window thickness

- Assuming operation at 1.2 atm, hemispherical Al-alloy windows, and "canonical" safety factor of 4,

$$t \approx 2\, PR/S \approx 2 \times 0.12 \text{ MPa} \times 0.3 \text{ m} / 300 \text{ MPa} \approx 240\ \mu\text{m}$$

(Determination of exact thickness awaits detailed design and finite-element analysis)

$\Rightarrow$ Negligible effect on beam given 175 cm of LH_2 per absorber

Minicooling: Simpler alternatives?

- Does it make sense to operate two “15´ bubble chamber equivalents” for this purpose?
  - While LH_2 capital and operating costs not show-stoppers, desirable to minimize operational effort/safety concerns, maximize reliability

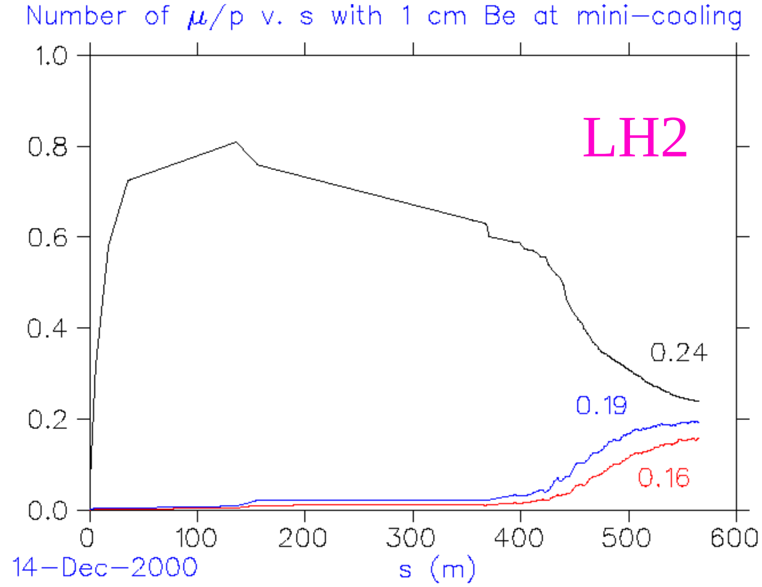
  ⇒ Why not minicool with water, liquid methane, solid lithium, or beryllium?

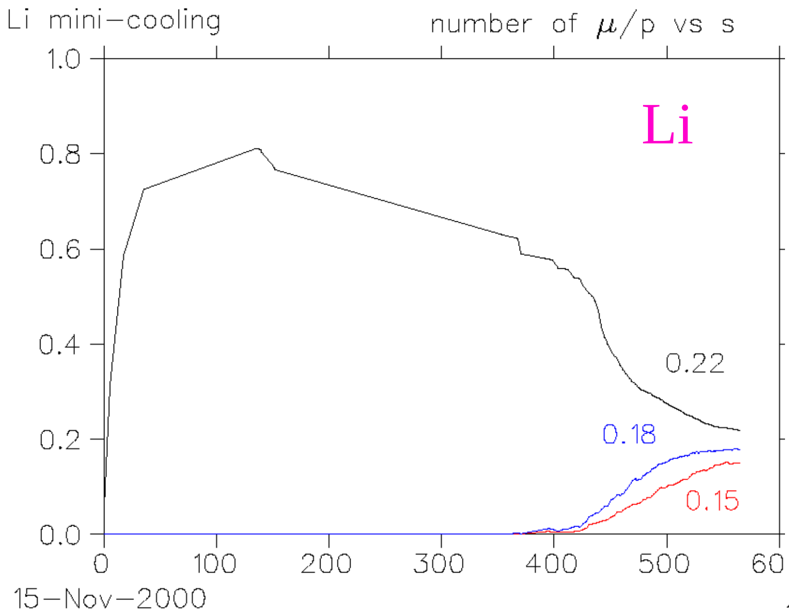
Mat'l	ΔE_min (MeV)	Length (cm)	$\%X_0$
LH_2	50	175	20
LiH	50	38	35
Li	50	57	37
CH_4	50	49	45
Be	50	17	48
H_2O	50	25	70

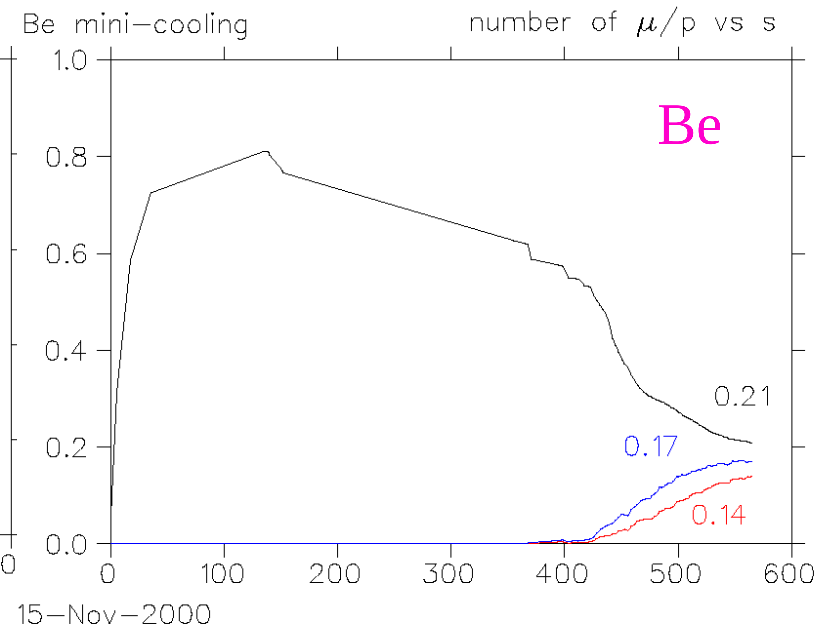
- Comments:

1. Liquid methane slightly better than beryllium
2. Liquids should give easier power handling by circulation
3. Solids require liquid cooling

Minicooling material comparison





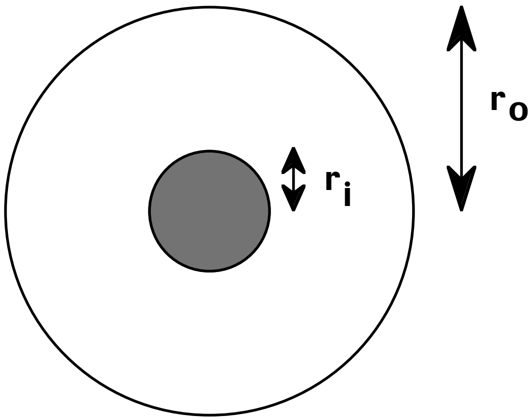


→ Li costs ≈5% in μ/p, Be ≈10%

– BUT: could raise B field to compensate

Solid minicooling: Heat transfer guestimate

- Approximate as 2D problem with heat applied in small inner core:



$$\Delta T \approx P/(2\pi kL) \ln (r_o/r_i)$$

(Neglect T dependence of $k \Rightarrow$ overestimate ΔT)

$k \approx 70$ W/m·K (Li) 200 W/m·K (Be)

say $P/L \approx 55$ W/cm (conservative)

$r_o/r_i \approx 5$ (conservative?)

$\rightarrow \Delta T \approx 20$ K (Li) ≈ 7 K (Be)

$\Rightarrow$ Water-cooling around perimeter should suffice

Minicooling – Conclusions:

1. LH_2 minicooling appears feasible and affordable
2. But hazardous and complicated
   - would increase operational difficulty & diminish facility reliability
3. Understanding multi-kW heat transfer in LH_2 requires more study
4. Should consider alternatives: Li, LiH, CH_4, Be

MCS in Strong Solenoidal Fields

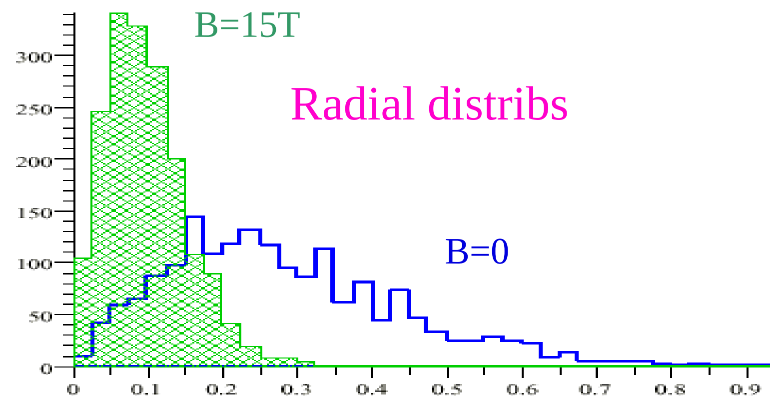
- Clear that in sufficiently strong solenoidal field, Coulomb scattering will be suppressed:
  - Consider $\lim_{B \to \infty}$: all charged particles must travel along field lines

  $\Rightarrow$ MCS suppressed completely!

- Effect not modeled in Geant, nor in Moliere theory!
  - Moliere model assumes linear transport between scatters
- P. Lebrun: MUCOOL Note 30:
  - brute-force "mm-by-mm" Geant sim of Rutherford scatters

Emittances after 32 cm of LH2
(starting with pencil beam)

Field	ϵ_{nC}
0.	27.7 ± 1.3
15 T., homogenous	11.8 ± 0.4
15 T., AltSol	12.2 ± 0.4



- How big is effect for Double-Flip ($B_z \leq 7$ T)?

We don't know! (But, will improve *e.g.* Double-Flip w.r.t. SFOFO)

New idea: Gaseous absorber?

([L. Lederman,] R. Johnson, & DMK, IIT – MUCOOL Note 195)

- LH_2 absorbers mechanically complicated, scattering in windows limits cooling performance

  ⇒ Why not high-pressure, gaseous-H_2 absorber?

  – Could improve cooling performance by

    1. Less scattering
    2. Shorter lattice → less μ decay
    3. More-adiabatic μ energy loss/gain processes

- Problem 1: don't want material at high-β points of lattice

  – BUT: long-solenoid lattices have ≈ constant β!

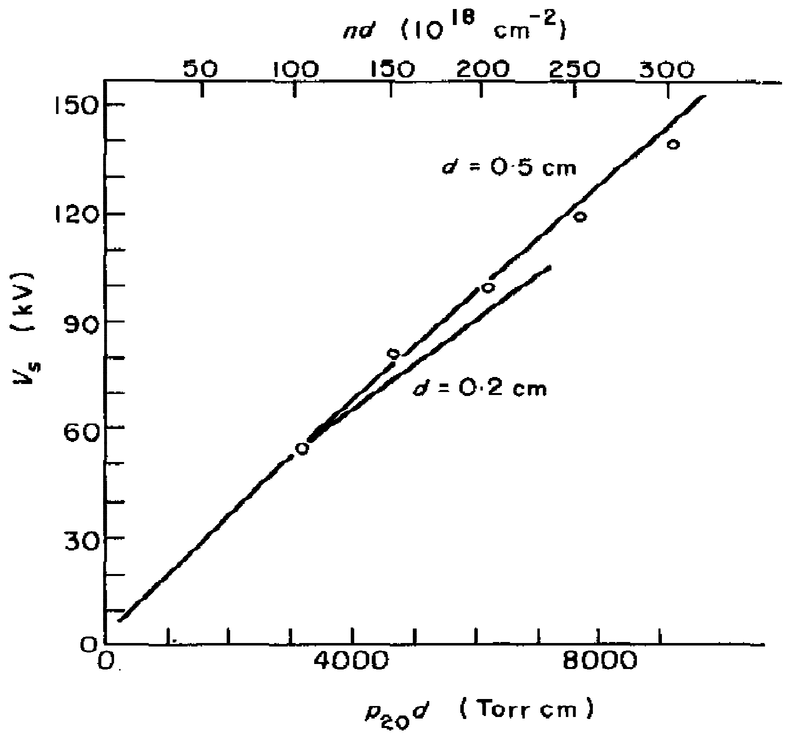
- Problem 2: avoiding windows means gas inside RF cavities

  → HV breakdown?

  – BUT...

Gaseous absorber? (2)

- High-pressure H_2 gas is established way to suppress HV breakdown:



Breakdown voltages in hydrogen (Müller, 1966. permission of Springer–Verlag)

—— Müller (1966)
○ Félici and Marchal (1948)

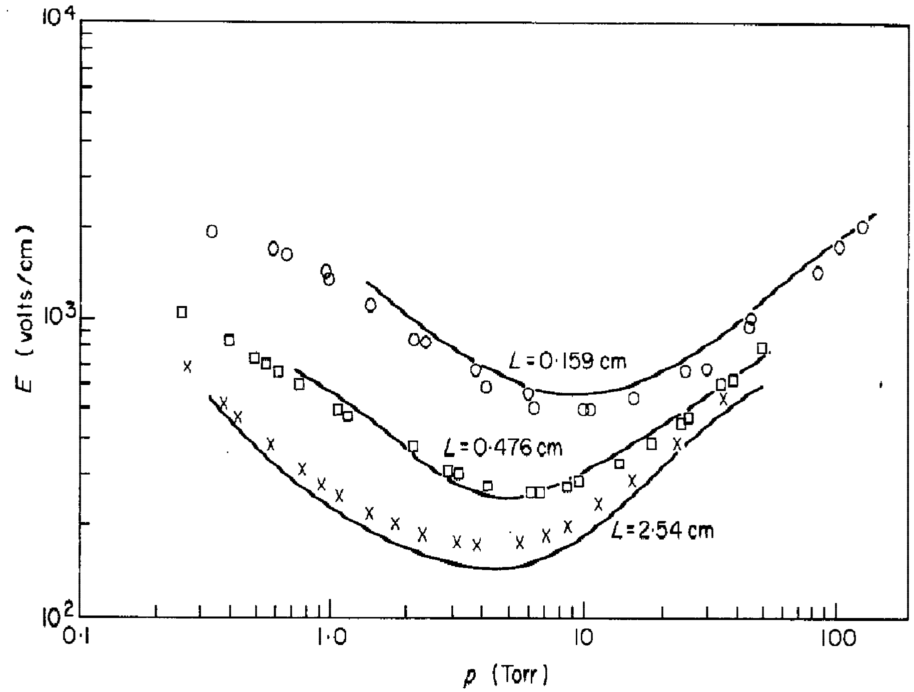


Figure 8.13. Theory and experiment compared for hydrogen at 2·8 GHz (MacDonald and Brown, 1949. Reproduced by permission of The America Physical Society)

– Paschen's Law: $V_s = 0.448\,(nd) + 0.6\,(nd)^{1/2}$ (need to confirm in our regime)

$\Rightarrow$ breakdown suppressed for $P \gtrsim \begin{cases} 40 \text{ atm (room temp.)} \\ 10 \text{ atm } (LN_2 \text{ temp.}) \end{cases}$

$\rightarrow$ To match absorption to RF gradient, need $P \approx 23$ atm at LN_2 temp.

$\Rightarrow$ Could raise gradient as well, possibly $\times\, 2$ (power limited)

Gaseous absorber? (3)

- Problem 3: need thick windows at two ends
  - BUT: preliminary estimate says effect small:

    1.6-mm Al exit window $\rightarrow \; \Delta\varepsilon_n \approx \beta_\perp \dfrac{(14\,\mathrm{MeV})^2 t}{2\beta^2 p_\mu m_\mu L_R} \ll 1\%$
  - while $GH_2 \rightarrow \varepsilon \downarrow 15\%, \;\; \mu/p \uparrow 10\%$ (V. Balbekov)
- Possible side benefit: gas-cooled cavities more efficient
  - $\times \frac{1}{2}$ in power at LN_2 temp?

$\rightarrow$ Conclude: more work needed, but looks interesting so far

Gaseous absorber? (4)

- Questions GH_2 R&D program should address (R. Johnson):
  - > Are the published breakdown voltages correct? Do expected operating conditions affect breakdown (ionizing radiation, RF frequency, external *B* field, surface materials, Be windows)?
  - > Can ion/electron-absorbing dopants improve breakdown behavior?
  - > Do we know how to build windows to work in these conditions (both vacuum and RF transition)?
  - > Are dark currents suppressed with GH_2?
  - > Does GH_2 have unexpected RF-power absorbing characteristics?
  - > Can the cavities be operated at lower *T* to reduce RF power (or to increase gradient at same power)?
  - > What is the optimum temperature, considering engineering, RF efficiency, windows, and gradient?
  - > Is there a cryogenic solution for efficient integration of cold RF, cold gas, and SC solenoids?
  - > If the cold RF doesn't work, is there a way to use a cylindrical ceramic insert?
- We expect GH_2 to work, but need actual tests to allay these concerns
  - – aim: identify 1st-stage R&D program soon, commence tests in FY02

Shaped LiH absorbers?

- Fabrication of LiH shapes assumed feasible (for *e.g.* emittance-exchange wedge absorbers)
  - Can exist in principle
  - Believed to exist for bombs (LiD)
  - "Helge Ravn has a piece in his office"

- Power handling (rough overguestimate as for solid minicooling):

  $\Delta T \approx P/(2\pi k L) \ln(r_o/r_i)$, $k \approx 6.49$ W/m·K, say $P/L \approx 50$ W/cm and $r_o/r_i \approx 5$

  $\rightarrow \Delta T \approx 200$ K *vs.* m.p. = 680°C

  $\Rightarrow$ looks OK

- Fabrication technology dangerous
  - reacts with H_2O, releasing hydrogen and igniting

  $\Rightarrow$ need to form in inert atmosphere, cool with kerosene or freon or what?

- Available commercially as powder or small chunks

  $\rightarrow$ I have found no vendor willing to manufacture large shapes

  - please let me know if you know of any!

Summary:

1. No show-stoppers
2. Some interesting technology being developed
3. LH_2 absorber R&D could be completed within 2 years
4. Minicooling probably better done above LH_2 temperature
5. GH_2 may offer improved cooling performance (or same performance at less cost)

Open questions:

1. How to model improvement in cooling with absorber at high B_z?
2. Still looking for LiH!